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Wireless sensing system for land movement monitoring and landslide detection

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Submitted in partial fulfilment of the requirements for
EQC Biennial Grants Programme 2014
Project Ref: 14/670.

Abstract

Land deformation monitoring - one of the most important aspects of landslide monitoring - provides an important basis for identifying landslide risk. This project has developed a wireless sensing system for the early detection of landslide risk. The types of sensors used in current practice provide valuable data related to landslides, but incur costs in excess of US$300,000 per site - limiting their deployment to only very high-risk sites. Our system utilizes low cost GPS chips (around $100/sensor) and, powered by renewable energy, can be deployed in large numbers over areas that are potentially vulnerable to landslides. Each self-powered sensor records its location periodically and transmits the GPS data wirelessly to a remote collection centre for processing. Taking advantage of the similarity in wireless channel conditions of sensors within close proximity, we are able to accurately compute the relative displacement between any two neighbouring wireless sensors without the need to determine the exact locations of the sensors. Even under harsh conditions where only intermittent GPS data are available, we are able to achieve sub-centimetre accuracy based on our outdoor tests in New Zealand and also at the LuShan landslide site in Taiwan.

Acknowledgments

The successful execution and completion of this project would not have been possible without the help of the following:

Dr Linus Wang of National Chi-Nan University, Taiwan. Dr Wang provided invaluable help to this project in the onsite testing at the LuShan landslide site and helped us maintain our system; his hosting and care for Jonathan Olds when he visited Taiwan in June/July 2014 is very much appreciated.

Dr Quincy Wu of National Chi-Nan University, Taiwan, for his help in setting up the network link from the router at LuShan site via the Internet all the way back to New Zealand. That network link had been instrumental in enabling us to collect GPS data from the sensors deployed at LuShan.

Dr Bryan Ng of the School of Engineering and Computer Science, Victoria University of Wellington, for his assistance in the supervision and mentoring of Jonathan Olds when the project leader was away in Japan during June to August 2014.

Tim Exley of the School of Engineering and Computer Science, Victoria University of Wellington, for his assistance in the implementation of the sensor nodes, including procurement of parts and components, ruggedization, etc.

And, most importantly, to EQC for providing the grant to carry out the research. Without the financial support from EQC, this research would not have been able to progress so rapidly, if at all.

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Chapter 1

Introduction

A key aspect of landslide detection is land deformation monitoring, which provides the basis for identifying landslide risks. Land deformation monitoring is useful for mitigation of threats to human life, property, infrastructure and the environment typically in mountainous and hilly regions. Some examples of sites that might benefit from land deformation monitoring are volcanoes, slopes prone to landslides, glacial flows, fault lines, subsidence, and large man-made structures such as dams and buildings to name a few. In this project, we focus on landslides although the system that we have developed can just as easily be deployed for the other types of sites and scenarios.

The monitoring of landslide movement patterns remains a challenge despite recent availability of techniques such as laser-based geodetic techniques, different Global Positioning System (GPS) and ground-/satellite-based radar [13, 14]. Most, if not all, existing techniques in use rely on the availability of accurate location information of sparsely deployed monitoring points in the landslide region together with data from other sensing devices [7]. While these provide valuable data related to landslides, their use incur costs in excess of US$300,000 per site, thus limiting their deployment to only very high-risk sites.

The system we have developed utilizes low cost GPS chips (around $100/sensor) that can be deployed in large numbers over areas that are potentially vulnerable to landslides. Each sensor records its location periodically and transmits the GPS data wirelessly to a remote processing centre. Taking advantage of the similarity in wireless channel conditions of sensors within close proximity, we are able to accurately compute the relative displacement between any two neighbouring wireless sensors without the need to determine the exact locations of the sensors. When all the relative positions of sensors are correlated to one or more sensors with known locations, e.g. survey point, we can create a map of the entire region being monitored. The system is able to detect any displacement between two nodes with a precision of 4 mm 2DRMS[1] based on our outdoor tests in New Zealand and Taiwan.

While this may not be as accurate as sophisticated hardware currently in use, it can provide an indication to warrant deployment of more accurate systems. The low cost of such as system would be a great advantage for widespread deployment for quick identification of potential trouble spots and/or provide early warning over vast regions. The increased spatial density achievable with this system can also provide high resolution monitoring data that assist in the understanding of landslide dynamics, which can enhance slope management and provide better forecasting and prediction of landslide behaviour.

In Chapter 2 we summarize the project goals and tasks as proposed in the grant application. Chapter 3 discusses the project execution and achievements, and in Chapter 4 we give our conclusions and discuss ongoing research as well as future plans.

[1] 2DRMS, twice the Distance Root Mean Squared, is a single number that expresses the 2-dimensional accuracy with 95% probability [1, Appendix D].

Chapter 2

Project Goals and Tasks

The aim of our project is to develop a wireless sensor network that monitors gradual land movement / deformation over time and can be permanently deployed with little to no maintenance. One of the critical issues with any remote monitoring system is the availability of power. We address this issue using renewable energy but cannot follow current practices of using disproportionately large renewable energy devices to ensure continuous power supply. While partly alleviating the power availability issue, we then need to develop a technique/algorithm that achieves the necessary level of accuracy, from raw GPS data acquired by low cost commodity GPS chips (costing around $100 per unit) operating under harsh conditions with intermittent GPS data due to sporadic power availability.

2.1 Project Objectives

2.1.1 Objective 1: Self powered low-cost wireless location sensor

The first objective is to build a low-cost wireless location sensor that can be deployed in large numbers on areas vulnerable to landslides. The unit must be able to operate for long durations without the need to manually replenish its power source. Existing landslide monitoring systems using wireless sensor networks are battery-powered and continue to face the problems related to maintenance and battery replacement [2].

The goal is to provide dense spatial location information of the land area over time so that gradual movements that are precursor to landslides can be detected early; other components like inclinometer and accelerometer can be added subject to available energy resources.

2.1.2 Objective 2: Accurate relative positioning algorithm

Our second objective is to develop a novel approach of mapping out the location of sensors without requiring accurate location information from sensors. This will reduce the cost and energy requirements of the GPS unit, both of which increase with its positioning accuracy.

Each wireless sensor merely takes GPS readings and sends the data wirelessly to the base station, which then forwards the data to a remote collection centre where mathematical computation is done using high-performance computing resources. Within or at the edge of the sensor deployment area, we can have one or more sensors with accurate known locations, e.g. a survey point, from which all other sensors' locations can be iteratively determined using these (reference) sensors as starting points. Even without known reference points, displacement between sensors can still be accurately detected and serve as an indication of land movement.

2.2 Tasks

To achieve the project objectives, we have defined the following tasks:

2.2.1 Task 1 – Wireless location sensor network development

In line with project objective #1 (subsection 2.1.1.), we will design a GPS-based wireless sensor node that is powered by energy harvesting using photovoltaic technology, i.e. solar panels. The key constraint will be the limited energy that can be harvested and stored, making it a challenge to keep the GPS receiver operating continuously without having to resume from a cold-start each time the energy storage is used up. To make the unit feasible for rapid deployment, ideally without any onsite configuration, the unit must be compact and robust – we are aiming for a box of dimensions around 12cm by 10cm by 10cm, essentially limiting the solar panel to not more than $200cm^2$. With this unit attached to a spike, it can be easily and quickly deployed over the monitoring area at the desired inter-node distances, e.g. between 50m and 200m.

Subtask 1.1 – Wireless node design, implementation and functional testing. This involves the fabrication and assembly of the node comprising a small GPS unit, compact solar energy harvester, power management, wakeup circuit and low-power wireless transceiver. Functional testing validates that the node is able to operate under prevailing weather conditions, including both favourable sunny weather as well as adverse weather like rainy and cloudy conditions where light intensity is low. A critical requirement of the node is the ability to continue operating throughout the night; it is expected that the night duty cycle will be lower than that of the day. Relaying of sensor data across multiple sensors to the base station will also be tested.

Subtask 1.2 – Base station design, implementation and functional testing. The base station serves as the data collection point for the sensors in the network. It has a reliable power supply, wireless transceiver for communication with the sensors, wired/wireless Internet connection, sufficient local disk storage and interface to rain/moisture/humidity gauges.

Subtask 1.3 – Weather proofing, ruggedization and outdoor onsite testing. Upon the completion of subtasks 1.1 and 1.2, the wireless sensor nodes and base station will be installed in weather proof containers. The first phase of the outdoor testing will be conducted under controlled environments within Victoria University of Wellington (VUW) to ensure that the entire system is operating as designed. The second phase of testing will be done at the Utiku landslide in central North Island, New Zealand.

Subtask 1.4 – Field tests in Taiwan at the Lushan landslide site. As part of our MoU with the College of Science and Technology, National Chi-Nan University (NCNU), Taiwan, we have been collaborating with Assoc Prof Quincy Wu in networking research and, since May 2013, Dr Linus Kuo-Lung Wang has been assisting us in this project by providing us with live GPS data logs from measuring stations at the Lushan landslide site [4]. This has enabled us to test the accuracy of our inter-sensor displacement algorithm (see Task 2).

2.2.2 Task 2 – Inter-sensor displacement algorithm design & implementation

In line with project objective #2 (subsection 2.1.2.), we will develop the algorithm and implement software to perform the mathematical manipulations used to compute the relative displacement between an arbitrary pair of neighbouring sensors.

Subtask 2.1 – Algorithm design, validation and optimization. To develop a mathematical algorithm for computing the inter-sensor displacement that accounts for the similarity in wireless channel conditions experienced by neighbouring GPS receivers. A preliminary design has been validated under ideal conditions (prior background work) with the data coming from both GPS receivers currently used for landslide monitoring, as well as from low-cost GPS receivers producing inaccurate data that do not meet the positioning accuracy needed for landslide monitoring. This algorithm needs to be further refined and, more importantly, optimized to work under realistic monitoring scenarios where data sets may be incomplete due to:

(i) Wireless transmission problems, which can result in loss and/or corruption of data sent from sensors to base station; wireless communication is highly susceptible to environmental interference, especially during adverse weather conditions like rain. We aim to alleviate (if not totally eliminate) this problem in our protocol design (Task 1, cf: subsection 2.2.1), failing which, the inter-sensor displacement algorithm must then handle.

(ii) Missing GPS readings due to sensors not having enough energy to operate; while photovoltaic energy harvesting technology is one of the most well developed and advanced energy harvesting technologies available, the amount of energy that can be harvested is still dependent on environmental conditions. Dealing with missing data in wireless sensor networks is a well-studied problem and there are many published techniques that we can utilize to address this problem [9].

Subtask 2.2 – Location data analysis and expert validation. With the data collected from the sensors, we first compute the relative positions between pairs of neighbouring nodes. Within or at the edge of the sensor deployment area, we deploy one or more sensors with accurate known locations, e.g. a survey point or at existing high-accuracy GPS stations located in the landslide region, from which all other sensors locations can be iteratively determined using these (reference) sensors as starting points.

2.2.3 Task 3 – Network optimization and sensor data analytics.

The key constraint in any remote monitoring system / network is the power supply and reliability of the data retrieval system. In order to ensure sustained operation without the need for regular maintenance, energy harvesting (EH) technologies have been widely used. However, in current systems, the size of the EH platform is comparatively large and therefore limits the number of units that can be deployed. To provide a high spatial density of sensing, we plan to use low-cost compact devices powered by EH but, due to the size constraints as noted in subsection 2.2.1, the EH capability is also significantly reduced. This gives rise to interesting research problems which this task will study:

(i) Single hop transmission to base station vs multi-hop relaying of information across sensors to base station – multi-hop relaying saves energy (per node) and when combined with data fusion can increase the transmission efficiency [11]; the disadvantage is that it introduces more opportunities for transmission errors to occur as the data is sent multiple times. Single hop direct transmission from sensor nodes to base station requires more energy per node but reduces the possibility of wireless transmission error; however, in a dense network with many nodes, it will increase the contention among nodes and also result in transmission errors.

(ii) Collecting few samples reliably or more samples unreliably – this is the prevailing tussle between traditional sampling techniques and current big data approaches. For our network scenario, we need to decide whether we want to use the limited energy supply to take few GPS readings and transmit them reliably to the base station, or take more frequent GPS readings and transmit them with a tolerance for a portion of the data to be lost; data loss in the latter case can result from the node running out of energy after taking GPS readings and not being able to transmit them.

2.3 Summary

In this chapter, we have summarized the objectives and associated tasks undertaken by the project. In the next chapter, we will discuss the project execution and achievements.

Chapter 3

Project Execution and Achievements

The project execution was planned for a duration of 12 months and the key members are project leader Winston Seah and project member Jonathan P. Olds. Jonathan Olds was the postgraduate student who undertook the research and development of this project as part of the Master of Engineering (ME) degree candidature. His scholarship covering tuition fees and stipend were funded by this project, and he was awarded the ME degree with Distinction for the work carried out. Jonathan Olds' ME thesis [8] provides all the technical details of this project. Here, we will only provide an overview of the key details from the project execution and achievements perspectives.

Variations to the original project schedule were required in order to accommodate the onsite testing in Taiwan. Taiwan is prone to typhoons with a season lasting approximately from June to October. It was hoped that heavy rain due to tropical cyclones might cause land deformation that we could measure. Instead of testing in New Zealand first, then Taiwan, we swapped the onsite test venues. An extension of 4 months was also granted by EQC for the project to complete the onsite testing in New Zealand. The original and revised project schedule is shown in Figure 3.1.

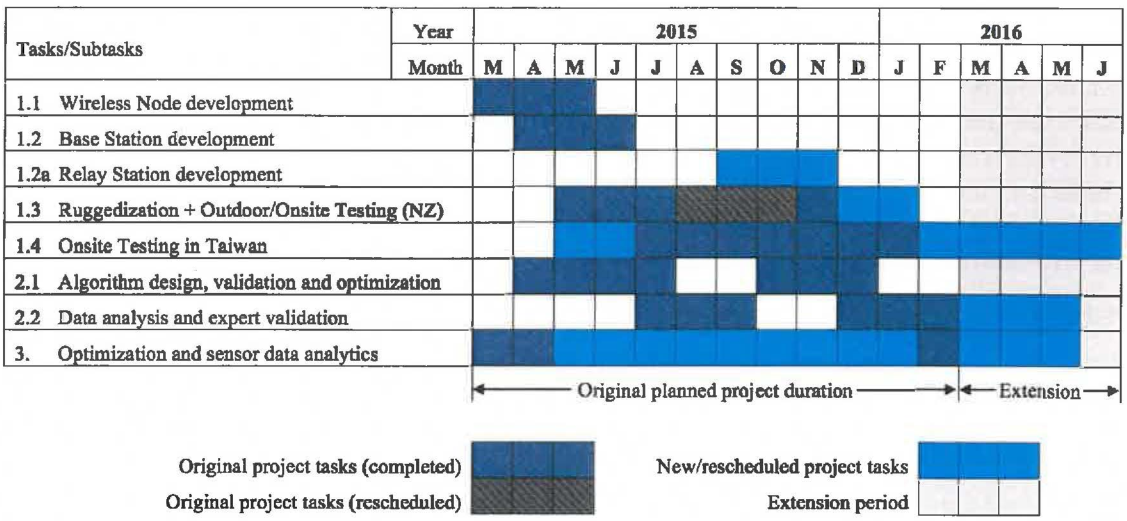

Figure 3.1: Project schedule

3.1 Task 1 – Wireless location sensor network

The project benefitted from the prior work done by key members, namely, Winston Seah (project leader) and Jonathan P. Olds (Master of Engineering student). Learning from the development of the earlier prototype, Jonathan Olds has been able to quickly develop an improved model of the wireless sensor (Figure 3.2 (left)) with significant improvement on energy harvesting and power management efficiency, accomplishing Subtask 1.1. Subtask 1.2 to build the base station (Figure 3.2 (right)) was also completed ahead of schedule. The first phase of Subtask 1.3 was completed according to plan, involving the ruggedization and outdoor functional testing of the sensors and base station, but the second phase on onsite testing in New Zealand was postponed (as Jonathan had to travel to Taiwan soon after to run onsite tests.) In April 2014, we sent four (4) sensor units and one (1) base station unit to our collaborator Dr Linus Wang in National Chi-Nan University (NCNU) in Taiwan for the onsite testing (Subtask 1.4).

Figure 3.2: Sensor Node (left) & Base Station (right)

Dr Wang and his students deployed our sensor nodes on the Lushan landslide site after conducting a series of tests in their laboratory to ensure the nodes are fully functional. The LuShan site is a known high risk landslide site on a hill above the town of Lushan in Taiwan's mountainous Nantou region. It is a site studied using satellite imagery, aerial imagery, laser survey and GPS. The active movement zone approximately covers 1 km^2 and resembles the shape of an inverted "V" starting at the top of the hill (Figure 3.3.)

The sensor nodes (orange circles #274, #275, #276 and #277) were deployed alongside retro reflectors used for laser based land deformation monitoring using a total station by NCNU. A permanently powered **base station** was placed on the hill, designated as node #1 (orange oval marked as "Router") and it performs the following functions:

(i) **sink** or **collection point** for the data obtained by the sensor nodes;

(ii) **router** to send the data via a 3G modem back to us in VUW via the Internet for processing; and

(iii) **GPS node** itself to obtain satellite observations.

The base station was mounted in a large pre-existing weatherproof metal cabinet box with mains outlet sockets inside. When Jonathan Olds visited NCNU in June/July to conduct onsite testing and validation, he was hosted by Dr Wang who provided us with invaluable assistance. At the site, Jonathan discovered that some of the nodes suffered intermittent

Figure 3.3: LuShan testbed site (courtesy of NCNU)

interferences to their wireless communication, most likely due to vegetation and foliage, e.g. node #277 as shown in Figure 3.4. To overcome this problem, Jonathan later built repeaters and sent them to NCNU, which were then deployed (red circles #101 and #104); this accomplished Subtask 2.1(i).

Figure 3.4: Vegetation around node 277 (Circa 28/8/2014, Courtesy of NCNU)

Onsite testing in New Zealand (second phase of Subtask 1.3) was carried out after tests in Taiwan. Unfortunately, due to unfavourable weather conditions and other logistics issues, we were only able to conduct onsite tests at Paekakariki where we simulated land movement by changing the nodes' positions in small increments. Testing at Utiki landslide in central North Island will be carried out later as part of our ongoing research.

3.2 Task 2 – Inter-sensor displacement algorithm

This is the core Intellectual Property (IP)[1] developed by this project. The inter-sensor displacement algorithm is called the Code-Float-Fix-Sidereal (CFFS) algorithm, which is a static relative positioning solution algorithm designed for nodes deployed in a harsh environment, communicating data over lossy wireless links. The nodes are powered by photovoltaic energy harvesting and small in size (as per our objectives), designed for detecting slow land movement / deformation over a long period of time. CFFS consists of four stages: code, float, fix and sidereal filtering. The code stage makes the first location estimate from the GPS data acquired by the sensors and each subsequent stage (float, fix and the sidereal) is designed to produce a more accurate position solution than the previous stage. The last stage, sidereal filtering, is used to improve inter-day solution precision and also alleviate multipath.

To find a relative positioning solution for two receivers A and B, Figure 3.5 shows the distribution of the algorithm over different devices and where the data enters the algorithm. The GPS receivers on the sensor nodes can be regarded as data sources supplying the algorithm with its data. This data contains code, phase, time, and navigation information. The node sections of the algorithm take the raw data, process it, and then send the processed data to the main section, via the "Router" across the Internet to a remote server (in NZ.) Each node contains different phase, code and time data while navigation data are common to all nodes.

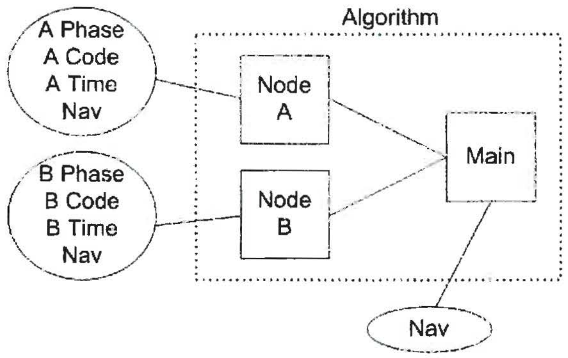

Figure 3.5: Algorithm distribution and data in flow

To keep the data flow between the node sections and the main section of the algorithm to a minimum, navigation data and code observations are not passed between the nodes and the main section. The information that is sent from nodes to main component of the algorithm are wrapped phase observations extrapolated to a common second based epoch $\hat{\phi}_B^S(t)$, the satellite number S, the receiver number B and the time t (accurate to a second) that these observation estimates are for. In addition, occasionally averaged autonomous code based solutions $\bar{\mathbf{X}}_B$ are passed to the main section along with the receiving number B, as depicted in Figure 3.6.

A key advantage offered by our algorithm is the ability for it to operate, i.e. compute the relative location, with intermittent GPS data, while existing systems require continuous availability of high quality GPS data. We compared CFFS with open source global navigation satellite system (GNSS) packages RTKLib [10] and GPSTk [15], as these were the only two open source GNSS packages freely available that supported singleband phase based

[1] Details of the algorithm are not included for confidentiality reasons as we are in the process of filing for a patent. Jonathan Olds' ME Thesis will also be withheld from public access for 1 year from the date of this report.

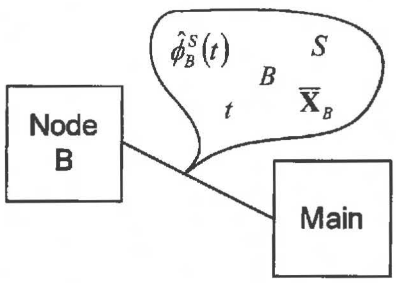

Figure 3.6: Data passed from node to main section of the algorithm

relative position solutions, similar to our approach. First, we show that CFFS is comparable to these solutions when continuous good quality GPS data are available. We used two months of high quality data obtained from GPS receivers, the first located at Te Papa museum and the second at Wellington Airport. The data were obtained from the RINEX data archive of Land and Information New Zealand (LINZ) [5]. The data rate was one epoch every 30 seconds. The baseline between these two receivers was around 4 km. To achieve a fair comparison, we use only data that represent singleband GPS receivers (as CFFS is designed for such a system) and also implemented a version of CFFS without the sidereal filtering, which we denoted as "JAC". For GPSTk, we used an application that has been developed using GPSTk, called "DDBase". The full CFFS algorithm with sidereal filtering is denoted as "JAC-MM", although we note that RTKLib and GPSTk can only be fairly compared with JAC as they do not have sidereal filtering. The results of our comparison using continuous high quality data is shown in Figure 3.7 with all approaches producing comparable accuracy.

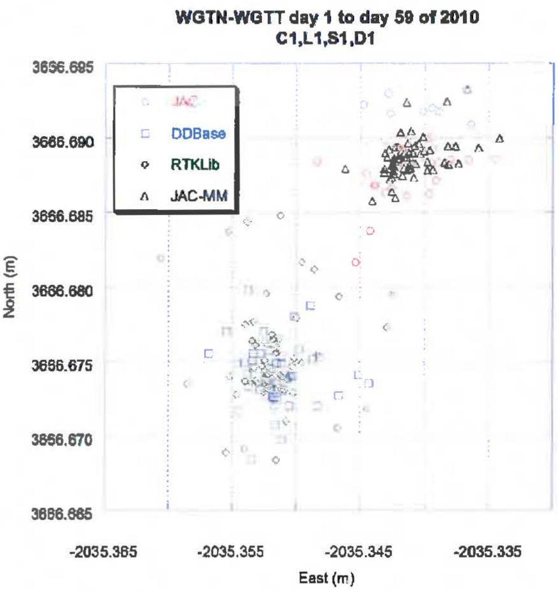

Figure 3.7: Relative positions using high quality data

For our target scenario, where nodes are powered by energy harvesting and the GPS data from nodes are sent via wireless links, it is inevitable that there will most likely be fewer GPS data, fewer and more intermittent GPS data, increased multipath, and generally poorer quality data. To simulate this, we random discard 50% of the data from the previous scenario of continuous high quality data. The results of this simulated data loss test are shown in Figure 3.8. It is expected that RTKLib and DDBase failed because they are designed to work on continuous high quality data obtained from receivers that are continuously powered. However, it is more important to our project that our CFFS algorithm not only continues to operate, there is no degradation in the accuracy.

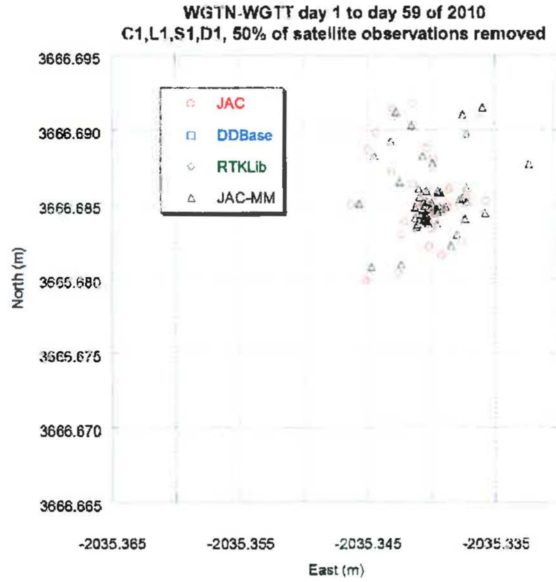

Figure 3.8: Relative positions with 50% data loss

Next, in order to validate the efficacy of CFFS, we need to determine whether or not any of the three candidate applications (JAC, DDBase and RTKLib) could obtain solutions of reasonable precision using real life intermittent poor quality data obtained from the GPS sensor nodes that we designed. We validated this by collecting real GPS data over a 1-week periods using our sensor nodes deployed in a test site at Paekakariki and processing the data using the different algorithms. As the nodes are powered by photovoltaic energy harvesting, they are only operational when there is sufficient sunlight; e.g. Figure 3.9 shows the number of hours per day for which a node's GPS receiver was active and successfully returned epochs when deployed at the Paekakariki test site for approximately two weeks in summer and then in winter. An example of the results computed by the three algorithms is shown in Figure 3.10.

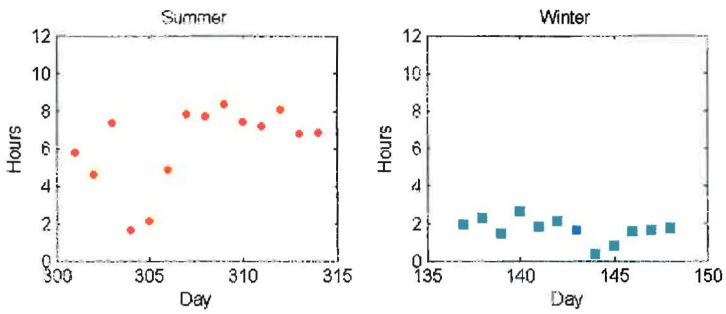

Figure 3.9: Number of hours a day that GPS receiver is active

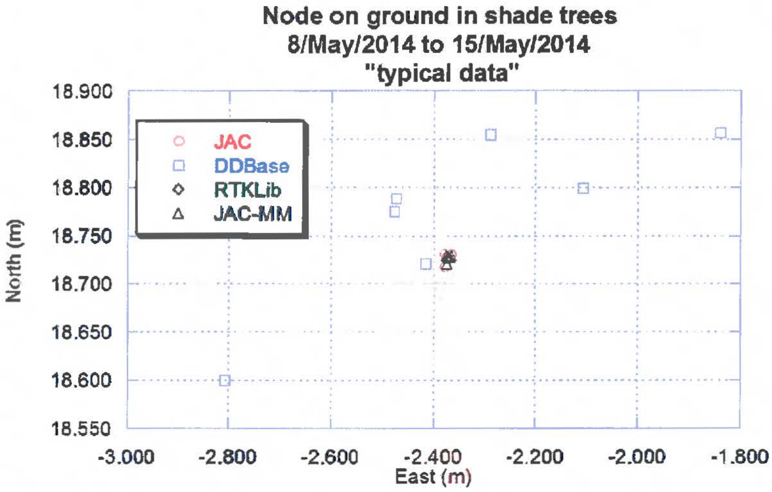

Figure 3.10: Outdoor test using our GPS sensor nodes collecting "typical" intermittent poor quality data. (One DDBase solution not plotted due to large variation)

3.3 Task 3 – Network optimization and sensor data analytics

This task is part of the project leader's wider research effort and undertaken by other post-graduate students. The two research problems identified, as well as another related problem, have been studied with the following achievements:

(i) **Contention among sensor nodes transmitting to a base station** – this problem was studied from the perspective of structural health monitoring where clusters of sensors are assumed to carry contextually similar data. When an event occurs, all sensors take readings and attempt to transmit their data. This will result in a sudden burst of data transmission attempts that cause severe contention and congestion in the wireless sensor network. The same congestion situation can occur in our scenario, e.g. at sunrise, when all sensors node become active at almost the same time after harvesting energy. To alleviate this problem, we proposed a cluster-based medium access control protocol that treats each cluster as a supernode, and show that by making all other nodes within a cluster abstain from attempting to transmit as soon as one node within the cluster has successfully transmitted, we are able to significantly improve the delivery probability and reduce transmission delays. A paper describing this research has been presented at the 13th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Mumbai, India, 25-29 May 2015, and published in the proceedings [12].

(ii) **Event reliability in wireless sensor networks** – An extensive survey of research was done and the results of the survey has been documented and published in a journal [6]. Ongoing research aims to design a technique for an arbitrary sensor node that is relaying packets to the sink to correctly identify packets (in its buffer) that contain data of the same event coming from different sensors.

(iii) **Ensuring full coverage for rare event sensing** – It is important for our sensing system to be able to promptly detect land movement that indicates high risks of a landslide occurring. While it is arguable that land deformation remains detectable after the initial onset of land movement, it may be too late to provide early warning. To provide full sensing coverage of the area being monitored, we proposed the Equitable Sleep Coverage Algorithm for Rare Geospatial Occurrences (ESCARGO) [3] for timely event notification where the network must also maintain connectivity at all times regardless of the significant energy cost of doing so. This non time-synchronized, fully distributed duty-cycling algorithm is shown to double the operational lifetime of battery powered rare event sensing networks with an optimised, low node density, non-random deployment scheme without compromising detection probability or notification delay. The algorithm is further shown to facilitate potentially indefinite coverage maintenance in sensor networks powered by small form factor solar panels without relying on charging efficiencies beyond the capabilities of existing technology.

3.4 Summary of Key Achievements

The real test of our system was the deployment in Taiwan at the LuShan landslide site, over the period when two typhoons occurred. Validation of our results by comparing against the measurements done using the NCNU laser based system confirmed that we are able to achieve an accuracy of 4 mm 2DRMS.

The design, validation and outdoor testing of the CFFS algorithm have been fully documented in Jonathan Olds' Master of Engineering thesis. His thesis was examined by a world renowned GPS expert, who awarded an "A" grade and made the following comment (image captured from a scanned copy of the thesis examination report):

> The quality of the work by Jonathon Olds is very, very impressive. The topic was challenging, and incorporated elements of low-cost GPS receiver selection, solar power generation controller, low-power/cost wireless communications, packaging the hardware for land deformation applications; development of carrier phase data processing software, multipath sidereal filtering, testing; and deployment on an actual landslide site in Taiwan. There is more than enough material to justify the award of the Master by Engineering degree.

Chapter 4

Conclusions

In this project, we have successfully designed, implemented and validated a highly accurate land deformation monitoring system. A novel small battery-less low-power solar-powered wireless GPS sensor node was designed and implemented using low-end uncalibrated low-cost components; the total cost per node is approximately US$100. To the best of our knowledge, this is the first such system that exploits the similarity in wireless channel conditions experienced by GPS receivers in close proximity to eliminate errors experienced by the signals in order to achieve highly accurate relative positioning.

As in all real projects, our original proposed schedule had to be revised in order to accommodate the onsite testing at an actual landslide site in Taiwan. While that has been completed successfully, it affected outdoor onsite testing in New Zealand; due to unfavourable weather conditions and logistics issues, we were unable to carry out tests at the Utiki landslide as originally planned. However, we were still able to conduct extensive outdoor tests at Paekakariki to validate the efficacy of our system. Testing at Utiki landslide will be still be carried out as it is part of the project leader's wider research goals. Despite this, we have achieved the objectives set out in the original project plan. Furthermore, our system and results have been validated by a world renowned GPS expert.

Moving forward, we are seeking IP protection (patent) for our inter-sensor displacement algorithm, called the Code-Float-Fix-Sidereal (CFFS) algorithm. We are also preparing a manuscript describing the algorithm to be submitted to a premier conference on pervasive computing, and an extended version of the conference manuscript for submission to a journal. However, both these manuscripts can only be submitted after the IP protection has been filed. Although this project has completed, there remains much more work to be done to bring this idea to full widespread deployment. Landslides continue to cause significant loss of lives and property globally especially in developing countries and we hope that this system can contribute to the reduction of the unnecessary loss.

Last, but not least, we like to extend our deepest gratitude to EQC for providing the grant to carry out the research. Without the financial support from EQC, this research would not have been able to progress so rapidly, if at all.

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